

# PILOT RESPONSE TO OFF-NOMINAL CONDITIONS IN MERGING AND SPACING OPERATION

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## Abstract

This paper examines pilots' responses during a human-in-the-loop simulation to off-nominal conditions. During the simulation pilots used advanced flight deck tools to achieve automated spacing and merging assignments while in cruise, and prior to performing a continuous descent approach (CDA) into Louisville International Airport. The off-nominal conditions were represented by sparse and dense weather-patterned perturbations. Simulation results showed that, for the baseline nominal condition, the pilot response and the operation worked as expected. However, during off nominal conditions, qualitative analysis of traffic scenarios and quantitative data showed that pilot behavior in deviating for weather was difficult to predict, and that pilots often took aircraft-centric strategies to make decisions. These strategies lacked a system-centric perspective that could have allowed them to explore the availability of less disruptive and safer options. These responses formed emergent behaviors that may not have been anticipated by the system, and, can be attributed to the mismatches between the pilot strategies, the intended system/operation functionality, and the procedures/environment. Collectively these mismatches created dispersion in the temporal spacing at the merge point prior to the descent, flight path stretches that are likely larger than required, higher workload, and ultimately unfavorable initial conditions for the CDA operation subsequent to the weather encounter. To further develop the interval managed CDA concept, a number of recommendations were provided for aligning these mismatches by considering the nature of the decision processes within the operational concept and incorporating them into automation designs, by developing a battery of off-nominal scenarios and by conducting simulations to model and specify what the system should and should not do.

## Introduction

In order to respond to the projected air traffic growth of 150 to 250 percent over the next two decades [1], new concepts of operation and new procedures enabled by advanced automated decision support tools are being proposed under the Next Generation Air Transportation System (NextGen) [2]. NextGen is a congressionally mandated initiative aiming to increase capacity, improve security and safety, and minimize the environmental impact of aviation. Among those modeling and researching new operational concepts, the study of off-nominal events during the operation has received great interest. Studying off-nominal events has been seen as very important because it can potentially provide insights into the operational concept and tools being developed, discover issues and behavior that are not anticipated or modeled, and provide valuable information for training and procedure development. Ultimately, being able to understand how a system behaves under unexpected conditions is a precondition for its field testing and eventual integration into actual operations [3]. The goal of this paper is to contribute to this understanding through an examination of a human-in-the-loop simulation (HITL) study in which off-nominal conditions were represented as weather perturbations at two different levels of severity, sparse and dense, along with a no weather (nominal) condition. The operational concept simulated is interval management during a continuous descent approach (CDA<sup>1</sup>), in which aircraft are merged behind a leading aircraft coming from another stream, follow the leading aircraft with an assigned temporal spacing interval, and fly an arrival. In this operation, the controller is responsible for merging the aircraft, maintaining their separation, and issuing spacing requirements to the pilot. The pilot is responsible for using automated

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<sup>1</sup> CDA is an aircraft noise abatement approach procedure that reduces noise and fuel consumption by descending the aircraft continuously at idle/low thrust without reverting to level flights.

speed guidance to make small adjustments to the speed in order to achieve the assigned spacing at the final approach fix. Both the controller and pilot are aided with ground-based and flight-based automation tools, which, in turn, are based on interval space management algorithms. The Airborne Spacing for Terminal Arrival Routes (ASTAR) developed by researchers at NASA Langley [4] or the CoSpace logic [5] developed by Eurocontrol researchers, are examples of two such algorithms. Extensive simulation studies [6-12] have shown that interval managed CDAs is a viable concept that yields good spacing performance and throughput, considerable noise and fuel reduction, manageable pilot workload, and high pilot acceptance. A recent simulation has also been conducted to explore the effects of off-nominal events introduced after the top of descent (TOD) [13].

Building on these works, this paper describes a HITL study that examined two human factors aspects of interval managed CDA: 1) the effects of different levels of pilot involvement on their ability to manage CDAs and interval spacing; and 2) the impact of weather perturbation on the interaction among the pilot strategies and goals, the intended system functionality, and the operation. The first aspect of the study is presented in a companion paper [14], which examines how well pilots could manage CDAs and interval management while using ASTAR automation. The results, reported for the CDA segment (after the top of descent) of the operation, showed that requiring the pilots to manually enter speeds into the autopilot, rather than having the automation automatically update the autopilot, frequently led to poorer energy management and

higher spacing interval errors at the final approach fix. This was traced to two main problems: poorer pilot compliance with the automated speed guidance and the lack of awareness of the energy state of the aircraft. One of the key contributing factors to these problems was the disruption to the initial spacing task caused by the weather perturbation introduced in the en route segment prior to the TOD. The effects of the weather perturbation on the pilot strategies and the resulting system behavior are the second aspect of the HITL study and will be presented in this paper.

## Description of the HITL Study

### Scenarios Design and Test Matrix

Scenarios were built to simulate interval managed CDAs into SDF along the CBSKT 1 arrival shown in Figure 1. The scenarios began with the experimental aircraft en route, and the weather, when present, was located between the aircraft and their TOD. Spacing clearances were issued and executed prior to deviation for weather so that the pilot could receive feedback regarding the amount of delay caused by their weather maneuver. After deviating for weather (when weather was present) pilots followed their lead down the arrival stream for a northern approach into runway 17 right. The trial ended when pilots arrived at the airport. Depending on the initial location of the pilot's aircraft in the arrival stream, pilots flew for a maximum of 90 minutes. All pilots flew together in an airspace managed by confederate air traffic controllers. Additional air traffic was flown by confederate "pseudo-pilots," to bring the total traffic load up to about 1.5-time current day traffic.

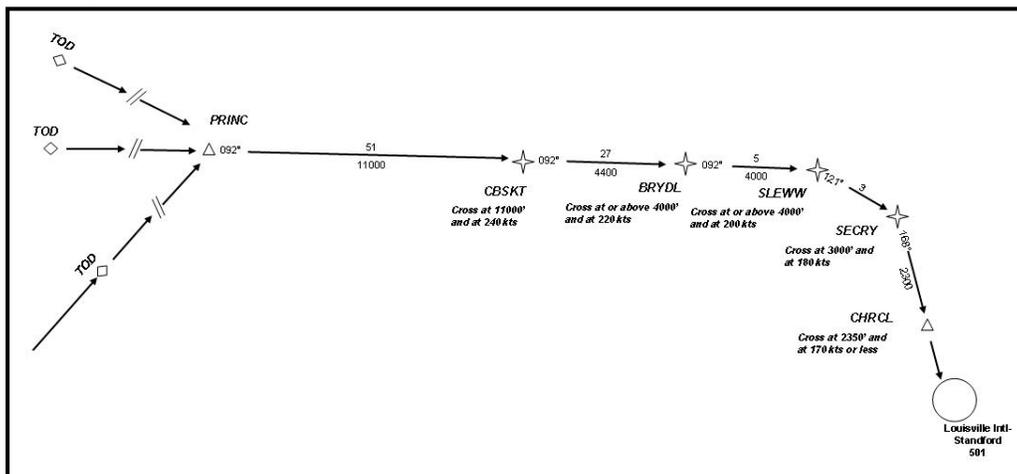


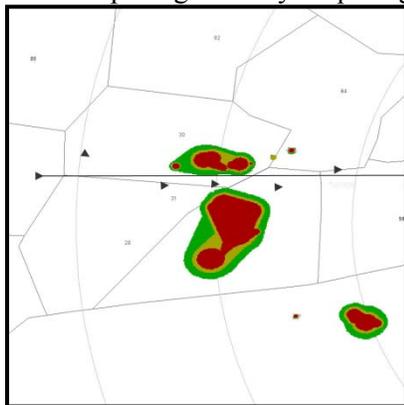
Figure 1. CDA Operation along CBSKT 1 Arrival

A 3 (En Route Weather: None, Dense Convection, Sparse Convection) x 2 (Pilot Instruction: Follow Speed Command, Pilot Discretion) x 2 (Speed Control: Automated, Manual) fully within subjects factorial design was used. The Pilot Instruction and the Speed Control manipulations were created to determine whether the speeds calculated by the automation had to be manually entered into the autopilot (Manual Speed Control); or if an option was available to automatically implement speed guidance (Automated Speed Control). The Pilot Instruction manipulation determined whether the pilot was told to faithfully follow automated speed commands (Follow Speed Command); or was given the latitude to overrule/augment this automated guidance with his or her own judgment (Pilot Discretion). For the purpose of this paper, these two manipulations were not considered because they did not yield any statistically significant results in the en route segment; however, they affected the CDA segment of the operation and are discussed in the companion paper [14]. The focus of this paper is the weather manipulation, which represents the off-nominal conditions occurred in en route segment. The weather manipulation was designed to generate a disturbance to the initial spacing task by requiring

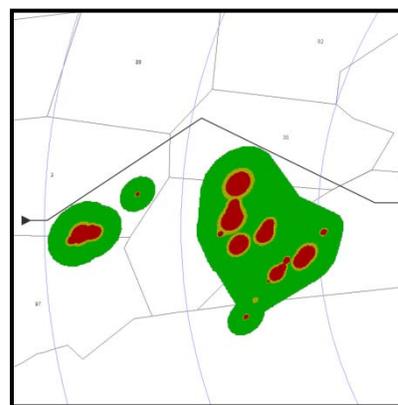
route modifications to avoid weather, and thereby place significant stress on the operation prior to the TOD.

### ***Off-Nominal Conditions***

In addition to a nominal no-weather condition, two off-nominal conditions were represented by two different convective weather patterns, Dense and Sparse. Figure 2 shows these patterns from a godseye top-down view (not from the flight deck point of view). These weather patterns were based upon, but not identical to, examples taken from historical Next-Generation Radar data. This data was used to create three dimensional storm objects which were then “viewed” by the pilots through simulated airborne radar (described in the next section). Within the radar image of the weather cell, the red zone represents high precipitation level, yellow represents medium, and green represents low. In the Dense weather condition, only a single static weather cell was presented and pilots were only able to make lateral deviations, rerouting north or south around the weather. In the Sparse weather condition, multiple static cells were presented to the pilots, providing them with options to fly paths in between cells.



**2(a) Sparse Weather**



**2(b) Dense Weather**

**Figure 2. (a) Sparse and (b) Dense Weather Patterns**

### ***Apparatus, Procedures, and Participants***

The study utilized a distributed simulation with participant pilots flying experimental aircraft with desktop 757-like simulators at the Flight Deck Display Research Laboratory (FDDRL) at NASA Ames Research Center, confederate air traffic controllers managing the traffic with MACS controller displays at the California State University Long Beach, and pseudo-pilots flying the rest of the

aircraft with desktop 757-like simulators from California State Universities Long Beach and Northridge, and from Purdue University. The pilot’s main simulation environment consisted of the Multi-Aircraft Control System (MACS) and the 3D Cockpit Situation Display (CSD). The MACS system provided a flight deck interface with mode control panels and display units normally found in current day Boeing 757/747s. A window on the MACS

interface displayed spacing clearances (aircraft to follow, and interval time-in-trail sent by a confederate air traffic controller) and buttons that allowed pilots to acknowledge reception of the clearance and to automatically load (or reject) this clearance. More information on the MACS is documented in [15]. The CSD (shown in top-down view in Figure 3 in order to best show the weather radar depiction) provided pilots with a 3D display of traffic information, a 2D display of weather information, an automated spacing tool and a Route Assessment Tool (RAT). The displayed, or displayable, traffic information on the CSD included 3D aircraft positions (shown as chevrons on the display), aircraft track angles given by the orientation of the chevrons, an altitude tail tag, and a graphical intended trajectory that could be shown for any displayed aircraft. Traffic information was presumed to be provided by an automatic dependence surveillance broadcast (ADS-B) from all aircraft in the scenario, with a simulated range of 160 nm from the broadcasting aircraft. The simulated airborne weather radar had a range of 180 nm, and the pilot could control the elevation of the radar with a radar tilt control. The RAT allowed a pilot to graphically construct new proposed flight trajectories, which were run through an automated conflict detection algorithm that provided visual alerts when proposed routes created traffic conflicts. The RAT also provided feedback on how much delay the proposed reroute would generate. The CSD was integrated with the Flight Management System (FMS) so that the pilot could execute the new route from the CSD.



Figure 3. CSD Shown in Top-Down-View

The automated spacing tool provided the speeds being recommended by the automation in order to meet the assigned spacing at the final approach fix. The recommended speed was shown on the CSD, together with information about how early or late an aircraft was relative to its assigned spacing interval. Using this tool, pilots could load the spacing clearances issued by ATC, engage the spacing automation, and monitor spacing status with a “spacing box”. The box indicates that the aircraft is early when it is ahead of the box, late when it is behind the box, and within spacing tolerance when inside the box. Based on the status, the pilot could make small adjustments to the speed in order to maintain the assigned spacing. The automated spacing tool is based on the ASTAR algorithm developed at NASA Langley. The reader is referred to [14] for a more complete description of the simulation environment and tools used in this HITL study.

Prior to experimental trials pilots received an introductory briefing and in-class training on procedures and tool use. This was followed by three practice runs. Pilot procedures included flying the most efficient and safest route while avoiding weather, and after passing the TOD, acquiring the same heading at the waypoint PRINC. PRINC was designated as the merge point to ensure that aircraft fly uniform descent profiles and achieve the restrictions at the remaining waypoints along the approach. Experimental runs took three days and a fourth day was scheduled for make-up runs. Pilots were debriefed at the end of each day. Eight commercial transport pilots with glass cockpit experience participated in the simulation and were compensated \$25/hr. Participants rotated into different aircraft on the arrival between trials and interacted with simulation software on single-pilot desktop PCs using standard keyboards and mouse inputs.

### Performance Measures

In order to understand the effects of the weather perturbation, the following quantitative and qualitative variables were obtained and analyzed:

1. Pilot response to the weather perturbation as observed by the rerouting decisions and the dynamics of the spacing between aircraft as a result of these decisions

2. The interactions between pilots and automation, potential pilot strategies, and the resulting behavior of the system/operation in comparison with the intended system functionality.
3. Workload comparison for three different weather conditions
4. Time interval between aircraft at the merge point
5. Amount of path stretch in different weather conditions

Additional data concerning the management of the CDAs were obtained and presented in the companion paper [14].

## Analysis and Results

In this section, the pilot response to the weather and the dynamics of the spacing will be first qualitatively depicted through three representative traffic situations. Then, quantitative results will be presented to further substantiate the effects of weather on pilot strategies, system behavior, and the CDA operation downstream.

### *Qualitative Depiction of Weather Disruption*

To qualitatively obtain the pilot response to the disruption caused by the weather, video, audio, and flight performance data of all 96 trials were reviewed for pilot maneuver choices. The operation in most trials appeared to work seamlessly, except for approximately 28 trials with weather present, in which it was observed that the weather perturbation caused different problems in spacing and in pilot response. These problems were reviewed for the weather's disruption on the operation and categorized in terms of spacing expansion or compression, re-assignments of lead aircraft and shuffling in aircraft order in the sequence, excessive path stretches around weather, and aggressive or late maneuvers affecting multiple aircraft. Among the categories of problems observed, three representative cases of traffic were selected to depict most of the problems, and sketched chronologically to illustrate the dynamics of the spacing among the aircraft.

Figures 4a, 4b, and 4c are snap shot illustrations of three different locations for a group of four aircraft (represented as triangles) maneuvering around a dense weather cell (represented by a gray oval). For

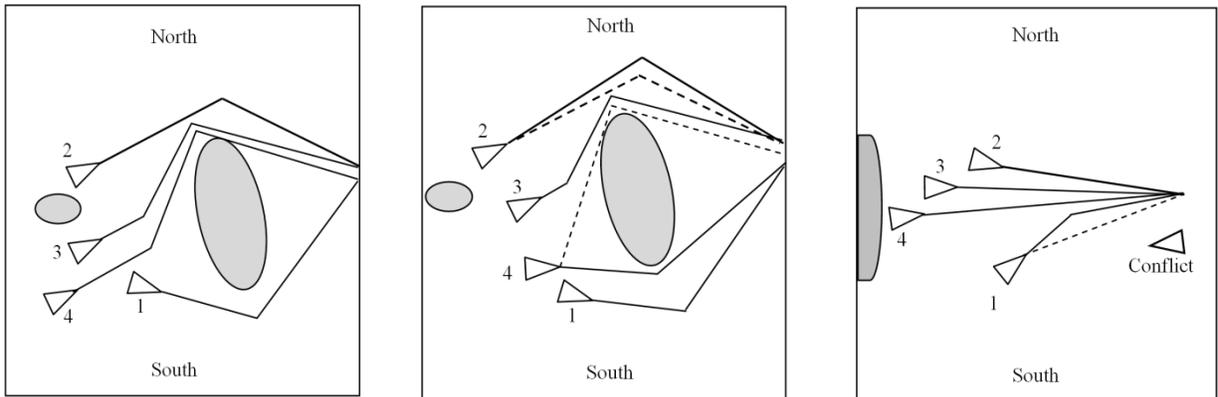
illustration purposes, the relative locations of the aircraft are not drawn to actual scale or the actual temporal separation. The aircraft leading/trailing order in the sequence is labeled as 1, 2, 3, and 4, where 1 denotes first in the sequence. In Figure 4a, first, aircraft 1 chose to maneuver to the south around the weather cell, putting it 20 s behind (late) where it needed to be in order to achieve its assigned spacing relative to its lead aircraft (not shown in the Figure). Following this, aircraft 2 maneuvered to the north around the weather, putting it 45 s ahead (early) of where it needed to be relative to aircraft 1. Then, aircraft 3, after apparently waiting until aircraft 2 had chosen direction around the weather, elected to follow its lead to the north around the weather, putting it 128 s behind its assigned spacing. Meanwhile aircraft 4, which was starting out 184 s ahead of where it needed to be, was maneuvering north around the weather towards its lead.

The evolution of the traffic is next shown in Figure 4b as the aircraft got closer to the weather. Aircraft 4 apparently decided that going north took it too far around weather, so it changed course to south and reduced its spacing error to 124s early (original and new paths are represented by dash and solid lines, respectively). Aircraft 2, also apparently realizing that it could improve its spacing, which was 45s early, widened its flight path relative to the weather cell and thus changed the spacing error to 4s late. However, this large change in direction eventually put aircraft 2 over 160 nm from aircraft 1 (who was going around the other side of the weather cell), and thus out of the 160 nm broadcast range of ADS-B. Aircraft 3, 140s late, requested a re-assignment but, for some unknown reasons, ATC denied the request until it got closer to the merge waypoint point PRINC.

Figure 4c shows a snap shot of the aircraft after they had passed the weather and were approaching the merge point. At this instant, aircraft 1 encountered a conflict so it had to deviate (original and new paths are again represented by dash and solid lines, respectively). This caused aircraft 2 to lose its spacing, probably due to one or more parameters in the spacing algorithm exceeding critical tolerances. The pilot of aircraft 2 contacted ATC to check on the status of its spacing, and ATC told him/her that he was now 40 miles, or approximately 266 s behind aircraft 1. At this time,

aircraft 3 was 90s late relative to its assigned spacing on aircraft 2, while aircraft 4 was 7s late relative to its assigned spacing on aircraft 3. As the aircraft

reached the merge point, aircraft 1 was 40s early, aircraft 2 was 14s late, aircraft 3 was 70s late, and aircraft 4 was 16s late.



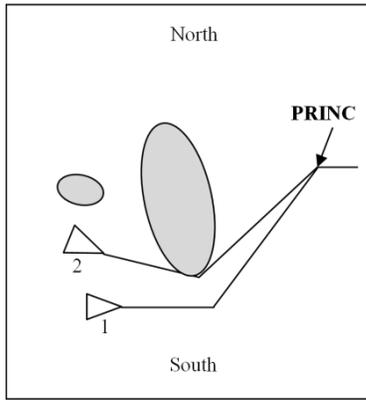
**Figure 4. Case Study 1: Aircraft's (a) Initial Diversion Paths, (B) Subsequent Readjustments, and (C) Relative Positions and Paths Past Weather**

The behavior of these aircraft showed that whether the pilots chose to follow their lead aircraft when going around the weather cell is difficult to predict. To make this decision, pilots appeared to use a wait-and-see strategy, in which they would wait to see which direction the lead would take before choosing their own re-route. Often the maneuver choices were performed early at the onset of the trial when the weather was relatively far away, and then routes would be modified a second time as the aircraft approached nearer to the weather. This is a method for refining a route in order to make it more fuel efficient. For the cases when the pilots chose to go around the weather on the opposite side of the lead aircraft (for efficiency and/or safety reasons), they showed that they had confidence in the automation, apparently assuming that the automation could maintain or regain the assigned spacing. However, as shown in the situation above, this assumption did not always work because the aircraft would be out of ADSB range or the spacing would become so large that the automation could not regain the spacing.

Written comments from the en route confederate controller (a retired FAA en route controller and instructor for students studying to become air traffic controllers) also indicated that pilot deviations around the weather have a large degree of unpredictability. The controller commented that,

“When aircraft were executing the weather deviation I delayed instructions until the deviation was completed as it is up to the pilot to choose the course around weather because the pilot weather depiction and the ATC depictions are different as well as the controllers/pilots opinion of best course.”

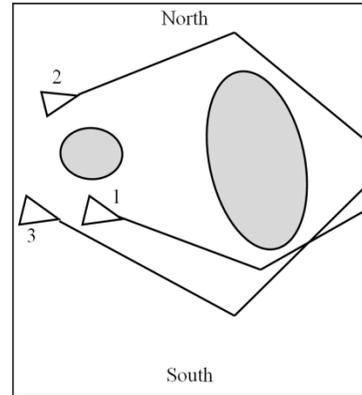
The situation in Figure 5 demonstrates another commonly observed behavior in which pilots compromised safety, probably because they wanted to faithfully follow the lead aircraft for efficiency reasons, or because they did not trust that the automation could achieve/maintain the assigned spacing if they decided not to follow the lead aircraft. As shown, aircraft 2 was 33 s late relative to the lead aircraft 1, so apparently it decided to catch up by following the lead in order to conserve fuel, however, doing this put the aircraft into the weather's low precipitation zone (green color) or very close to the medium precipitation zone. This behavior suggested that in the interaction between pilots and the automation, there was a mismatch between the pilot mental model and the automation due to the differences in pilot expectation of the automation and the automation's actual capabilities. Specifically, the pilot did not need cut close to the weather in order to catch up with the leading aircraft because the spacing automation could correct for the spacing gap by commanding the lead aircraft to slow down with speed adjustments.



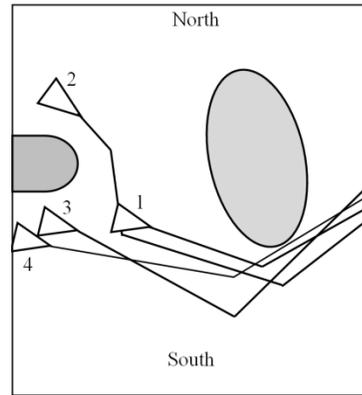
**Figure 5. Case Study 2: Aircraft Flying Through Weather's Low Precipitation Zone**

Combinations of complex interactions between pilots and pilots, and pilots and automation were also observed and illustrated in Figure 6. In Figure 6a, lead aircraft 1 was safely navigating south, aircraft 2 was deviating north around the weather with a 51s early spacing, and aircraft 3 was also deviating south around weather 14s early. At the next traffic snapshot shown in Figure 6b, aircraft 2 decided to make a late secondary weather avoidance maneuver in an apparent attempt to reduce the early spacing error with the lead aircraft, however this resulted in aircraft 2 then becoming 252s late, an overall worse spacing than before. This late secondary adjustment in turn resulted in a temporary display loss of spacing information for aircraft 2 and aircraft 3, requiring an overall slowing down in the flow of trailing traffic, with aircraft 3 now becoming 173s early. Aircraft 2 re-adjusted two additional times to reduce the spacing gap as it approached the weather. Aircraft 4's spacing was on time at this time. Figure 6c shows the situation when aircraft 2 was halfway around the weather and its spacing was 225s late, while aircraft 3 appeared to be closer to aircraft 1 than aircraft 2. Because of this, aircraft 3 received a command from the traffic controller to cancel spacing and maintain course. However, the pilot of aircraft 3 failed to cancel spacing, and instead increased speed from 250kts to 322kts! Consequently, this caused aircraft 3 to be 70s late, and aircraft 4 had to made adjustments to catch up. As the aircraft flew past the weather cell as shown in Figure 6d, aircraft 2 was re-assigned to follow aircraft 3, and aircraft 3 was told to follow aircraft 1 (In Figure 6d, the new aircraft order is represented by the number in parentheses). With the re-assignment of following aircraft 1 at the instant shown in the figure, aircraft 3 was 45s late in

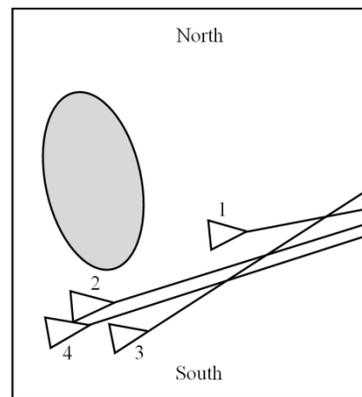
its spacing, so the pilot of aircraft 3 called ATC and advised that he would speed up to reduce the spacing. As the aircraft approached the merge point, the spacing performance of the aircraft were, on time (aircraft 1), 20s late (aircraft 2), 16s late (aircraft 3), and on time (aircraft 4), respectively.



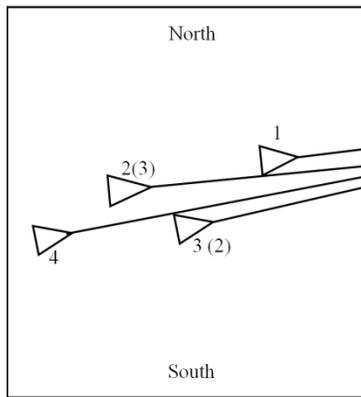
**6(a)**



**6(b)**



**6(c)**



6 (d)

**Figure 6. Case Study 3: Aircraft’s (a) Initial Position, (B) and (C) Subsequent Position Around Weather, and (D) Reassigned Order**

The behavior observed in Figures 6a-6d shows that the pilot choice of making a late deviation around weather in an attempt to maintain the assigned spacing came at the cost of slowing down aircraft assigned in trail, shuffling their positions, and increasing the number of adjustments that all aircraft have to make. In making this choice, the pilot may have overweighed the cues of the leading aircraft without knowing the position of the leading and trailing aircraft, and/or without taking into consideration the impact of this choice. This result suggests that the pilot took an aircraft-centric strategy to make decisions, and lacked a system-centric perspective that would have allowed him/her to explore the availability of less disruptive or non-disruptive options.

### ***Quantitative Analysis of Weather Disruption***

To further substantiate and quantify the described effects of the weather and the resulting pilot response during the CDA operations downstream (again see companion paper [14] for the CDA segment), quantitative results will be presented in this section. Figure 7 shows a histogram of the spacing at the merge waypoint PRINC for the three

different weather conditions. The no weather trials show tight clustering at 118 s. This spacing is consistent with the way the scenario was designed, in which the initial required spacing was 105 +/- 15 s at the start of the scenario (before PRINC) and 128.57 s at CHRCL (after PRINC). The weather trials show the expected dispersion of spacing intervals, with the dispersion being in longer intervals. There were a few cases in which the spacing became very large, exceeding 168 seconds. Overall, the dispersion in the longer intervals implies that the weather perturbation created an expansion in the spacing of the aircraft. The expansion is likely an artifact of two factors. The first is the strategy that the confederate controller used to create enough spacing buffer between aircraft. The controller reported that in order to ensure that the total space needed is available, he adjusted the position of the last aircraft in the sequence, and when the pilot deviations around the weather were completed, he would re-space the aircraft if needed. The second factor was the uncertainty in the position and spacing of the aircraft as they deviate for weather, which created a dynamic response in the spacing of the aircraft as described in the previous section. To account for the uncertainty and variability in the spacing, additional spacing was inserted.

Figure 8 shows the histogram of the path stretch for three different conditions. The path stretch was computed as the difference between original distance to the final approach fix and the distance that the plane flew. As shown, the disruption caused by weather perturbation can result in path stretches up to 78 nm long. The cases with large path stretches would in turn create unfavorable initial conditions for the CDA operations as the aircraft might need to speed up to catch up with the leading aircraft. This, however, leads to challenges for pilots in managing the speed and the energy of the aircraft while it decelerates along CDA. The challenges and consequences are discussed in detail in the companion paper [14].

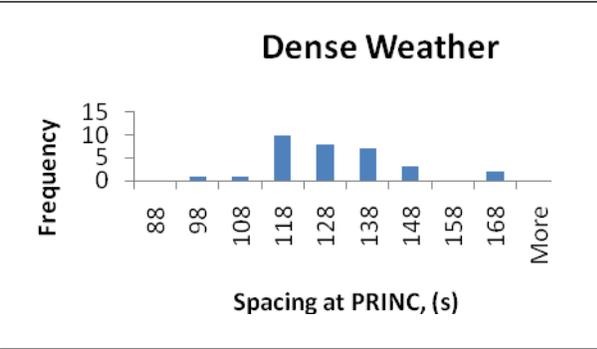
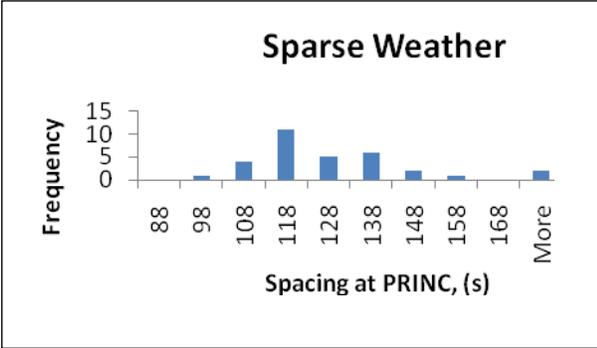
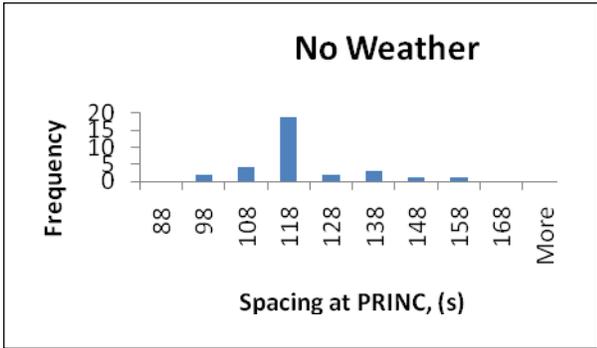


Figure 7. Temporal Spacing at PRINC for No, Sparse, and Dense Weather

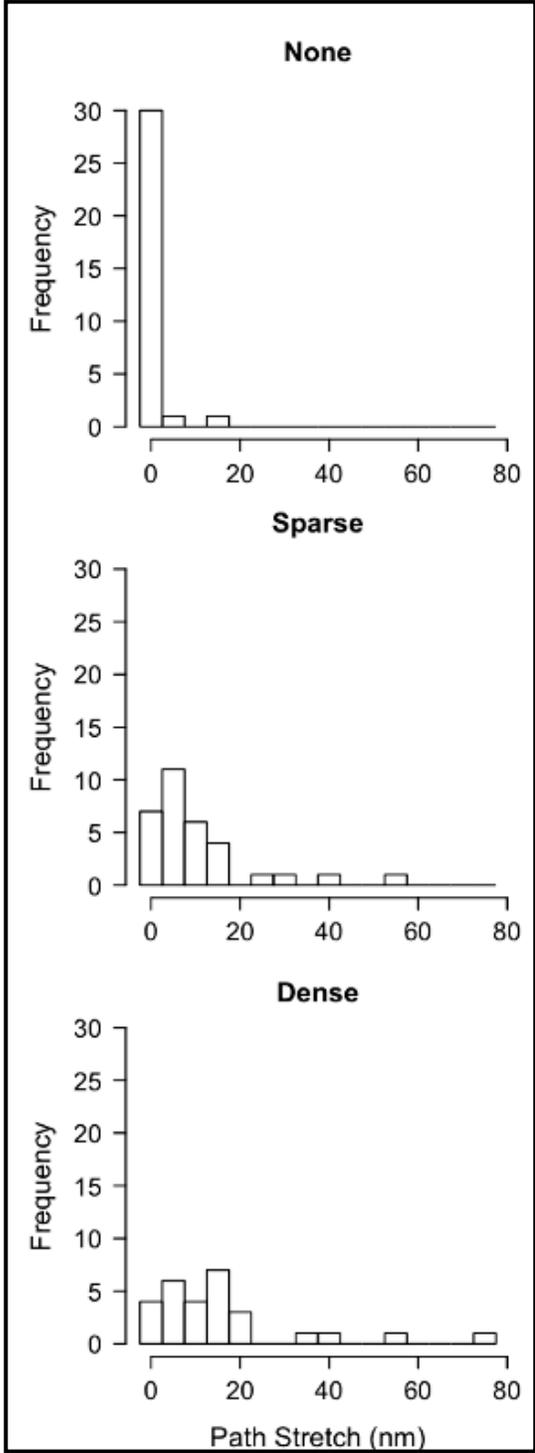
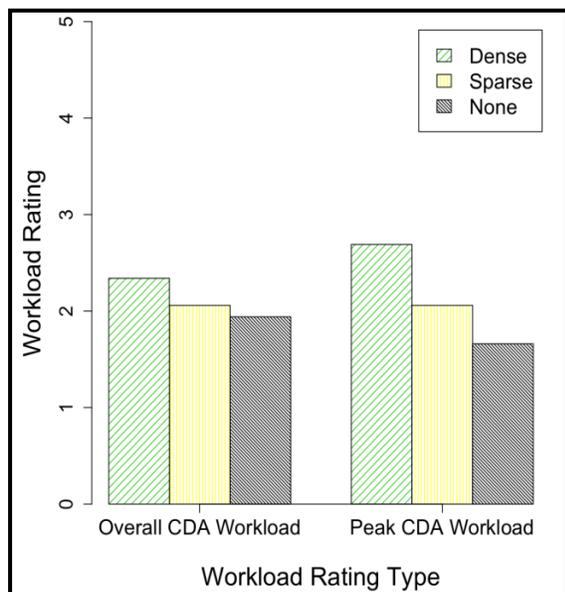


Figure 8. Path Stretch for No, Sparse, and Dense Weather

The pilot workload as a function of weather is shown in Figure 9. As hypothesized, the pilot workload for the dense condition was highest, followed by the sparse and no weather conditions. The range of the reported average workload ratings, from 1.7 to 2.7, indicates that the workload was at a manageable level. Consistent with this result, the confederate controller reported that workload varied greatly depending on the scenario from near capacity (for weather conditions) to well below capacity (for no weather conditions).



**Figure 9. Workload Ratings as a Function of En Route Weather**

## Discussion and Conclusion

The results obtained in this study highlight a number of important issues related to pilot response to weather perturbation during interval managed CDA operations. It was found that when the operation was disrupted by weather, there were mismatches between the pilot strategies, the intended system/operation functionality, and the procedures/environment. In interacting with the automation, pilots were faced with the decision of whether to trust the interval management automation to maintain the assigned spacing in the face of an array of complicating safety and efficiency factors such as: in-trail separation, immediate proximity to weather, fuel consumption, uncertainty with respect to the future separation from weather when going around it, and uncertainty about the overall evolution

and behavior of the leading and surrounding aircraft. It was found that the weather perturbation can create situations in which the spacing can be negatively affected regardless of whether the pilot faithfully followed the leading aircraft, or took a path different than that of the leading aircraft. If pilots do not fully understand the rationale and logic of the spacing automation and its limitations, then trusting the automation to be able to resolve a spacing error (i.e., being ahead or behind schedule), to regain a lost or interrupted spacing assignment, requires that pilots' high, albeit unconditional, confidence in the automation.

Compounding this problem was the observation that pilots tend to take an aircraft-centric view when maneuvering around weather. Without apparently fully understanding, or taking into account, the effects of his/her weather avoidance decisions, especially those that involved late deviations around weather, individual pilot actions were unpredictable and often led to undesirable consequences. These consequences included shuffling of aircraft order, an increased number of spacing adjustments leading to expanded spacing at the merge point, and ultimately to unfavorable initial conditions for the CDA operations. Collectively, these consequences are a part of emergent operational behaviors that may or may not have been anticipated by the system designer.

From a system perspective, one of the fundamental functionalities of an interval managed CDA operation -- maintaining spacing with the lead aircraft by having pilots make small adjustments to the speed with the help of automation -- was "stretched" beyond its intended scope. As shown in the study, in order to safely and efficiently navigate around weather, pilots had to take into account not only just the spacing with the leading aircraft, but also the interactive nature of their own actions affecting the other aircraft around them, and vice versa. For instance, if, in case 1, the deviation of aircraft 1 and 4 is north of weather (and the deviation of aircraft 2 and 3 is south of the weather), then aircraft 1 should be given spacing on aircraft 4 with the spacing increased to the proper amount. At some point past the weather, aircraft 2 and 3 can be re-inserted between 1 and 4. Similarly, the confederate controller also recommended that pilots should space on an aircraft that is two or three aircraft ahead of

them, instead of the one directly in front of them. The controller noted that controllers find this strategy an effective way to buffer the effects of transient spacing variations of the few immediately leading aircraft on a trailing aircraft.

From a procedural or operating environment perspective, the design of the interval managed CDA operation is a very human-centric process, in which different agents (i.e., pilots and controller) simultaneously interact to negotiate, execute, and monitor the operation. In the absence of the weather perturbation, the decisions made by pilots (and controllers) were based on established guidelines (that are codified as rules and procedures) and helped ensure the evolution of a smooth traffic operation. However, with the weather perturbation, the pilot decision processes for avoiding weather while maintaining spacing were unpredictable. Consequently, the intended behavior of the operation did not match that of the actual operation. As aircraft maneuvered around the weather, the nominal structured trajectory and the aircraft order often broke down. The subsequent shuffled aircraft order and variability in the spacing indicated poor, or poorly structured, coordination among the agents, and/or a lack of rules for balancing the interplay between the aircraft-centric actions of pilots and the overall system-centric goals of ATC/automation.

These findings provide important implications for the further development of interval managed CDA operations in off nominal conditions. In particular, in order to align the functionality specified by the designer, the strategies or mental models of the agents (i.e., pilots and controllers), and the operating procedures or environment, it is critical to consider two aspects: (a) the nature of the decision processes within the operational concept, and (b) automation designs that appropriately take into account these decision processes. With respect to the first aspect concerning decision processes, it is necessary to consider and identify the decision processes that can be represented by well defined rules or procedures, and those that involve intuitive judgment, uncertainty, or unpredictability that cannot be fully prescribed. For instance, the specific strategies or principles that the controller used to sequence and separate aircraft, and the rules/procedures codified in the automation algorithm, can be classified as well-defined

components of the system, whereas the behavior of the pilot in maneuvering around weather can be considered an ill-defined component inasmuch as this involves the unpredictability of human judgment and intuition. Decomposing the system into ill-defined and well-defined components will provide insights into the design of information sharing, and of function allocation, among the agents and the automation, and will help improve the operation's robustness and adaptability to weather perturbation.

With respect to the second aspect, design of the automation, it is essential that the human factors inputs are incorporated into the automation algorithm. It was found that in the presence of weather perturbation, having pilots manage the spacing by following the lead aircraft and making adjustments based on the speed provided by the spacing automation did not always work well. It would be worthwhile to consider integrating elements into the automation that are based on the same principles that pilots and controllers use. Such principles could include, for example, the spacing of an aircraft based on either the leading aircraft, or based on one or several aircraft that are ahead of the leading aircraft. The design of this logic would add flexibility to the control and spacing of aircraft and improve the operation robustness.

While the results, and their implications, presented in this paper are an initial effort to understand the effect of off-nominal conditions on pilot responses within an interval managed CDA operation concept, they suggest that a number of research avenues need to be further explored. The first avenue is the development of a comprehensive battery of off-nominal traffic, weather and equipment function scenarios presenting unexpected situations that have the potential to degrade system performance and create mismatches between the users' mental models, the intended system functions, and the environment. Second, methods for delineating and modeling the decision processes involved in responding to these off-nominal scenarios, and then incorporating these models into the automation design, also need to be investigated. Third, concept evaluation can be conducted by various synergistic types of simulations. For example, Monte Carlo simulations can be conducted to consider cases that involve large uncertainty in system components and stochastic processes,

whereas agent-based modeling and simulation can be used to obtain emergent behaviors that are otherwise not easily observable, and human-in-the-loop simulations can be used to study specific conditions of interest. Concurrently and/or iteratively performing these simulations in the evaluation of the concept will provide important insights for modeling and writing specifications for what the system should and should not do. Being able to capture and specify the system's nominal and emergent behavior is one of the key requirements for field testing or integrating the concept into NextGen's midterm and long-term plans.

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